Oil-water Interfacial Tension Effects on Relative Permeability Curves in Low-permeability Reservoirs

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Abstract

Relative permeability curves of low permeability cores with different permeability were obtained through displacement experiments, including water flooding and surfactant flooding. Changes of the relative permeability curves before and after injecting surfactants with different interfacial tensions were contrasted. The relative permeability curves of water flooding had the following characteristics: relatively narrower two-phase region, lower water relative permeability at residual oil saturation, higher residual oil saturation(37.6%, 39.7% and 40.5%, respectively), and lower ultimate oil recovery(only 37.3%, 27.8% and 23.6%, respectively). While oil/water interfacial tension decreased from 16mN/m to 7.1×10^{-4}mN/m, the two-phase region became wider, and residual oil saturation decreased. At the same time, water relative permeability at residual oil saturation increased, and ultimate oil recovery increased by 13.6%, 15.6% and 16.4% respectively. And the lower the interfacial tension is, the better the effect of enhancing oil recovery is. In general, surfactants have a great application prospect on the oil field development of low and extremely low permeability reservoir, and the oil-water interfacial tension should be reduced as far as possible.

Keywords

Low Permeability; Relative Permeability Curve; Surfactant; Interfacial Tension; Recovery

Introduction

Low permeability reservoirs have the main characters of thin pore throats, large specific surface area, low permeability and strongly Jamin effect (Zeng L.B., Qi J.F., and Li Y.G. 2007). The seepage rule of low permeability reservoirs does not obey the Darcy's law, and there is a threshold pressure gradient, which is different from that of middle and high permeable reservoirs (Yin D., Gao P., Pu H., and Zhao X. 2010; Zeng B.Q., Chen L.S., and Hao F. 2010). After injecting water, dispersed oil droplets remain in the pores of reservoirs, and cannot pass the minute pores. The oil phase of reservoirs flows by the way of small slugs or drops, instead of continuous flow. When the oil droplets and water droplets pass narrow throats, the injection pressure rises due to resistance produced by Jamin effect.The seepage channel of oil in low permeability reservoirs is very narrow, and the filtrational resistance is very high. Also, the diffusion speed of formation energy is very slow. So the ability to absorb water in the injection wells is quite poor, and the injection pressure is high. The production decreases in a much higher speed in the oil production period. Thus the effect of water flooding in low permeability reservoirs is not good enough to enhance oil recovery.

Recent research shows that surfactants can decrease interfacial tension, and improve the oil/water seepage characteristics, so they can reduce injection pressure and enhance oil recovery (Sun C.H., Liu W.D., and Tian X.C. 2009). The mechanism of surfactant active mainly includes: reducing interfacial tension of oil-water, altering the wettability of rock surface (Adibhatia B., and Mohanty K.K. 2007; Bortolotti V., Macini P., and Srisuriyachai F. 2010; Seethepalli, A., Adibhatla, B., and Mohanty, K. K. 2004.) emulsifying crude oil, increasing the surface charges, conglomerating oil drop, forming oil zone, changing

the rheology of crude oil and so on. At present, many scholars have done a lot of experimental studies about surfactants to improve the development effect of low permeability reservoirs (Adams W.T., and Schievelbein V.H. 1987).

Manrique et al. found that current waterflooding recover was only 40-50% of the OOIP because of microscopic oil trapping and macroscopic bypassing (Mantique E.J., Muci, V.E., and Gurfinkel M.E. 2006). Babadagli suggested the surfactant injection was recommendable in the pre-waterflooded unfractured zones as long as the proper surfactant type was selected. To use a surfactant solution for tertiary recovery, surfactant concentration, type and interfacial tension are important factors (Babadagli T., Al-Bemani A., Boukadi F., et al. 2005). Mohan studied the feasibility of oil recovery by surfactant flooding from an oil-wet carbonate reservoir. The unique features of the subject reservoir were high salinity and low permeability (2-5md). 80% OOIP was recovered using the surfactant which gave low interfacial tension (10^{-3}dynes/cm) in comparison to 60% from water flooding at similar pressure drops (Mohan K. 2009).

Oil/water relative permeability curves can show the relationship between relative permeability of oil-water two-phase and water saturation. A lot of reservoir information, including residual oil saturation, rock wettability, theoretical recovery efficiency, sweep area etc. can be obtained from the curves. Torabzadeh and Handy found that surfactants could be used with injection fluids to increase recovery efficiency of immiscible displacements through reduction of interfacial tension, and the oil-water relative permeability increased by decreasing interfacial tension at given water saturations (Torabzadeh S.J., and Handy L.L. 1984). Liu and Li found that reducing oil/water interfacial tension of low permeability reservoirs could reduce additional capillary resistance, as well enhance flow capacity of injection water, and increase relative permeability of water phase (Liu A.W., and Li X.W. 2006). Wang et al. believed that low interfacial tension could improve the values of oil-water relative permeability, thus making the intersection of oil/water relative permeability curves moves to the right, and decreases residual oil saturation (Wang Y. D., Wang S. H., and Jiang Z. J. 2004). Liu et al. thought that the decrease of oil/water interfacial tension could reduce additional capillary resistance (Liu Q., Dong M., and Ma S. 2006). So dispersed oil drops could flow through throats more easily. Water injection capacity as well as oil recovery could also be improved. To sum up, surfactants have great influence on the two-phase relative permeability and recovery efficiency of low permeability reservoirs. However, there is no certain conclusion for the relationships between the interfacial tension and those parameters of low permeability cores with different permeability.

In this paper, different oil-water relative permeability curves of low permeability cores with different permeability were drew in the course of displacement experiments. And the variations of relative permeability curves under different value of interfacial tension were discussed. Moreover, qualitative and quantitative evaluations of surfactant's ability to enhance oil recovery were conducted.

Materials and Methods

Materials

1) Experiment Materials

- Cores

In this study, natural low permeability cores of Shengli Oilfield were used, and the basic data are listed in Table 1.

TABLE 1 BASIC DATA OF EXPERIMENTAL CORES

Core number	**Length /cm**	**Diameter /cm**	**Gas log permeability /$10^{-3}\mu m^2$**	**Porosity /%**
Core 5-8	5.90	2.50	33.2	17.58
Core 62-3	5.78	2.51	7.30	15.65
Core 97-2	6.11	2.50	0.52	13.87

- Formation Water

The formation water of Shengli Oilfield was used which had the salinity of 1785mg/L.

- Simulated Oil

Simulated oil was obtained by mixing diesel and crude oil of Shengli Oilfield with the proportion of 4:6, and its viscosity was 2.28mPa•s at 50°C.

Interfacial tension between the formation water and the simulated oil was 16mN/m.

- Surfactant

Surfactant HFYQ-B was selected, and interfacial tensions between 0.2%, 0.25% HFYQ-B and the simulated oil were 0.0092mN/m, 0.00071mN/m, respectively.

- Experiment Apparatuses

Many apparatuses, including TX-500 spinning drop interface tensiometer, reservoir simulation displacement equipment, electronic balance, etc., were applied in the experiments.

2) *Experimental Methods*

Conduct displacement experiments to get the relative permeability curves of low permeability cores by steady state method and non-steady state method.

Experimental temperature was 50°C. Experiment procedures were as follows. And the flow chart is shown in Fig.1.

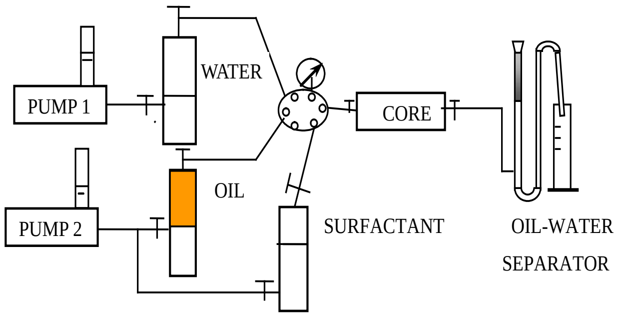

FIG. 1 FLOW CHART OF CORE DISPLACEMENT EXPERIMENTS

(1) Weigh the core after drying it, then vacuumize and saturate it with formation water. Weigh again to calculate the pore volume of the core.

(2) Drive the core with formation water at a constant speed of 0.05mL/min under a temperature of 50°C.

(3) Drive the core with the simulated oil to irreducible water saturation, age 24 hours, then record the volume of oil saturated, last but not the least calculate irreducible water saturation, and effective permeability of oil phase under irreducible water saturation.

(4) Non-steady state method (for cores whose gas permeability is higher than 5×10-3μm2).

- Set a certain pressure at the core inlet, and keep the pressure lower than the steady pressure when the effective permeability of oil phase was measured.
- Drive the core with the formation water. Record the cumulative oil production, cumulative fluid production and their corresponding inlet pressure during the displacement experiment. And record the oil production before water breakthrough time, and the accurate water breakthrough time.
- Calculate the oil/water relative permeability and the corresponding water saturation as well as the water ratio. Then draw the relative permeability curves.

(5) Steady state method (for cores whose gas permeability is lower than 5×10-3μm2)

- Inject the mixture of oil and water at a certain ratio into the core. Record the differential pressure and the flow rate of oil/water after the flow was stable.
- Get the water saturation of core by weight method. And calculate the oil/water effective permeability according to Darcy's equation.
- Then Draw the relative permeability curves.

(6) Wash and dry the core. Repeat the steps (1) ~ (5) of the experiment through changing with surfactants of different interfacial tensions. Likewise, draw the relative permeability curves, respectively.

Results and Discussion

The relative Permeability Curves of Cores with Different Permeability

The displacement experiments were conducted with the formation water, 0.2%HFYQ-B surfactant solution, and 0.25%HFYQ-B surfactant solution, respectively. Three cores were used in these experiments (as shown in Table 1).

Both core 5-8 and core 62-3 were measured by using the unsteady state method. The relative permeability curves of core 5-8 and core 62-3 under different interfacial tensions are showed in Fig.2 and Fig.3, respectively. Core 97-2 was measured by using steady state method. The relative permeability curve of core 97-2 under different interfacial tensions is showed in Fig.4.

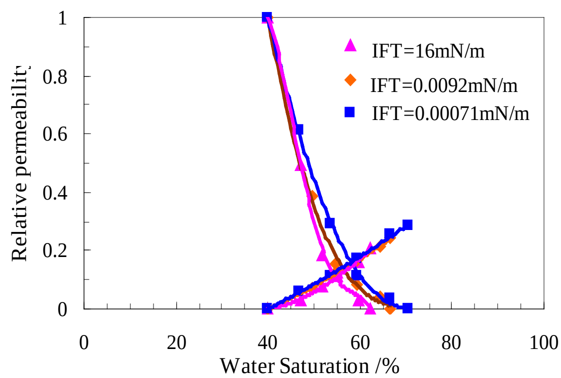

FIG. 2 RELATIVE PERMEABILITY CURVES UNDER DIFFERENT INTERFACIAL TENSIONS

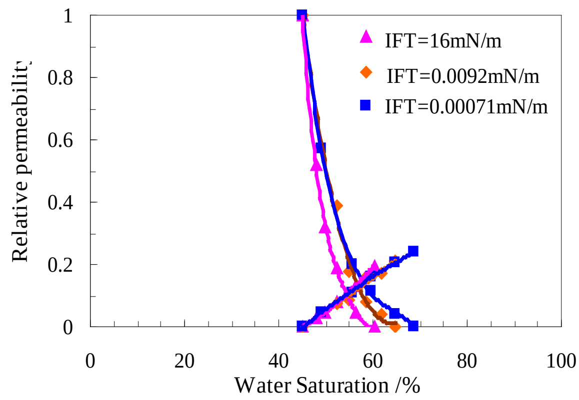

FIG.3 RELATIVE PERMEABILITY CURVES UNDER DIFFERENT INTERFACIAL TENSIONS OF CORE 62-3

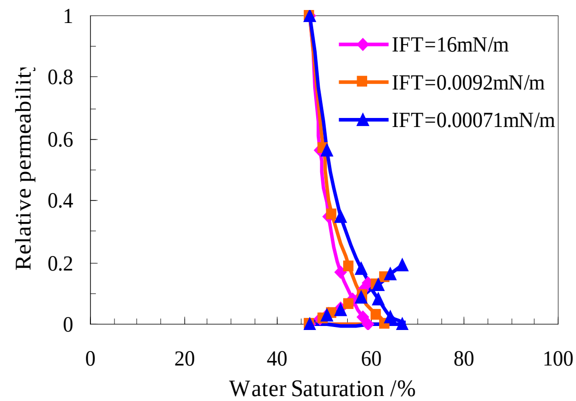

FIG. 4 RELATIVE PERMEABILITY CURVES UNDER DIFFERENT INTERFACIAL TENSIONS OF CORE 97-2

Through analysis of the Fig.2, Fig.3, and Fig.4, one can get the following conclusions:

(1) The two-phase region of relative permeability curves obtained from the displacement experiments using the formation water is quite narrow. And the relative permeability of water phase under the state of residual oil is low. The residual oil saturation of core 5-8, core 62-3 and core 97-2 is high, reaching 37.6%, 39.7% and 40.5% respectively. So the ultimate oil recovery of all the three cores is low, only 37.3%, 27.8% and 23.6% respectively (Table 2).

TABLE. 2 CHARACTERISTICS OF RELATIVE PERMEABILITY CURVES UNDER DIFFERENT FLOODING PATTERNS

Core number	Interfacial tension /(mN/m)	Residual oil saturation /%	Water permeability under residual oil	Ultimate oil recovery /%
Core 5-8	16.000	37.6	0.208	37.3
	0.0092	33.5	0.243	44.2
	0.00071	29.4	0.287	50.9
Core 62-3	16.000	39.7	0.196	27.8
	0.0092	35.1	0.213	36.2
	0.00071	31.1	0.238	43.4
Core 97-2	16.000	40.5	0.185	23.6
	0.0092	36.9	0.199	30.4
	0.00071	33.4	0.214	37.0

There are some reasons for these results as follow:

During the process of water flooding, dispersed oil drops remain in reservoir pores and cannot flow through minute pores. The oil phase flow in the state of small slug or dispersed drops, instead of a continuous state. When oil drops or water drops flow through narrow throats, the injection pressure would increase because of Jamin Effect. And water lock effect occurs during the operation in oil wells. The formation energy spreads slowly in low permeability reservoirs. The recovery of water flooding is low as a result.

(2) With the decrease of interfacial tensions of oil-water, the two-phase region increases, the permeability of water phase under the state of residual oil increases, and the residual oil saturation decreases. So the ultimate oil recovery is improved. For instance, when interfacial tension drops from 16mN/m to 7.1×10^{-4}mN/m, residual oil saturation of core 5-8, core 62-3 and core 97-2 decreases by 8.2%, 8.6% and 7.1% respectively, and ultimate oil recovery of core 5-8, core 62-3 and core 97-2 increases by 13.6%, 15.6% and 16.4% respectively (Table 2).

There are some reasons for these results as follows:

Surfactant can reduce interfacial tension and capillary resistance, make oil bead deform easily, and decrease the power on which oil droplets were emitted through the pore throat depending. It is easier for oil drop to change the shape of itself and flow through the throat. The residual oil saturation decreases greatly. And amphipathy of surfactant enables itself to absorb the surface of boundary layer of core, which can reduce the thickness of boundary layer liquid so that throat volume becomes lager and flow resistance decreases. Moreover, surfactant can not only reduce the adhesive resistance of oil film on the rock surface, but also emulsifies the oil film and impels it to fall off from the surface. Meanwhile, owing to the reduction of residual oil the flowing space of water phase increases gradually, so sweep efficiency is becoming larger, and the relative permeability of water phase becomes higher. In all, the lower interfacial tension is, the higher the extent of enhancing oil recovery is.

However the residual oil saturation has not dropped to zero when treated with surfactant of ultra-low interfacial tension. Analysis indicates that the emulsified oil droplets in narrower pore space may be displaced through the pore throat only when the lower interfacial tension is reached. In addition, the sweep volume of surfactant solution is limited. It is difficult

for residual oil saturation of low permeability cores to drop to a very low degree as a result. Therefore, further study should be focused on the lower oil-water interfacial tension and the sweep efficiency of surfactant solution.

(3)The relative permeability of oil phase increases with the decrease of interfacial tension, but the relative permeability of water phase (within endpoint) is not affected. Analysis shows that surfactant lowers the resistance of oil droplet flowing through the pore throat caused by Jamin effect, and increases the relative permeability of oil phase. On the other hand, the oil beads are produced from small pores of low permeability cores, so more and more residual oil begin to flow. The increase of flowing space of oil phase lead to the increase of oil relative permeability. However, the water permeability is not changed.

Comparison of Various Relative Permeability Curves

For the low permeability cores with different permeability, the relationship of residual oil saturation with oil-water interfacial tension is drawn in Fig.5. And the relationship of ultimate oil recovery with oil-water interfacial tension is drawn in Fig.6.

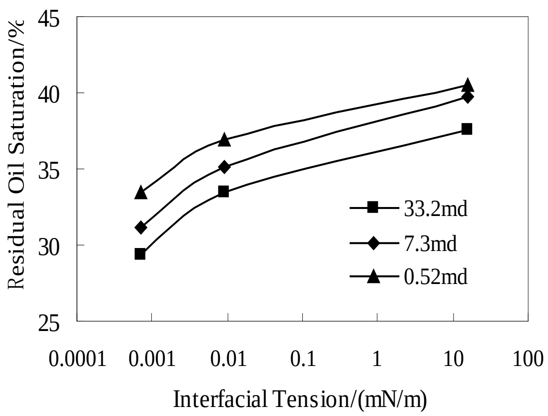

FIG. 5 CURVES OF RESIDUAL OIL SATURATION WITH PERMEABILITY OF CORE

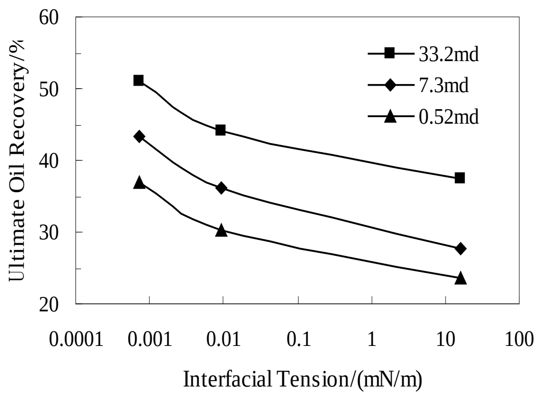

FIG. 6 CURVES OF ULTIMATE OIL RECOVERY WITH PERMEABILITY OF CORE

As shown in Fig.5, not only, residual oil saturation increases with the increase of oil-water interfacial tension, but also it increases with the decrease of permeability of the core.

Similarly, there is inverse relationship between the ultimate oil recovery and oil-water interfacial tension or permeability of the core in Fig.6.

Analysis, in general, the less the permeability of the core is, the narrower the average throats radius in core is, and the more complex the distribution of pore throat. The snap-off of oil resulting from the minute pore and throat is more serious, and the more dispersed oil drops remain in reservoir pores. So the Jamin effect is increased, and oil beads are more difficultly produced, resulting in higher residual oil saturation and lower ultimate oil recovery.

The relationship of water relative permeability at residual oil saturation with oil-water interfacial tension is drawn in Figure 7.

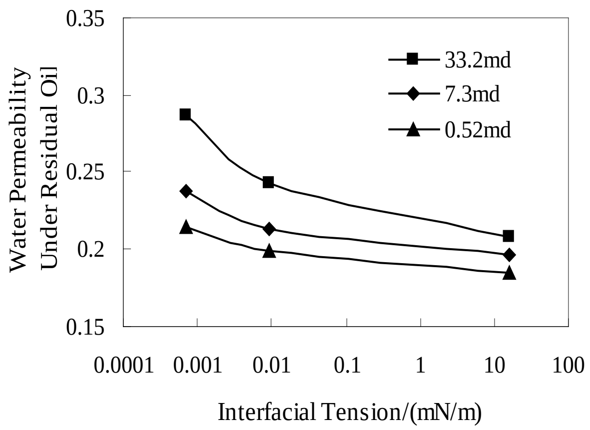

FIG. 7 CURVES OF WATER PHASE PERMEABILITY UNDER RESIDUAL OIL WITH PERMEABILITY OF CORE

As shown in Figure 7, not only, water relative permeability at residual oil saturation decreases with the increase of oil-water interfacial tension, but also it decreases with the decrease of permeability of the core. Analyzing its reason, the lower the permeability of core is, the higher the residual oil saturation is. So the flowing space of water phase is much smaller, and the amount of oil droplets trapped at pore throats is increased, and Jamin effect is increased. As a result, the water relative permeability at residual oil saturation is in a smaller level.

Conclusions

The relative permeability curves of water flooding had the following characteristics: relatively narrower two-

phase region, lower water relative permeability at residual oil saturation, higher residual oil saturation, and lower ultimate oil recovery.

At the same oil/water interfacial tension, residual oil saturation, water relative permeability at residual oil saturation and ultimate oil recovery decreased with the decrease of permeability of core.

With the decrease of oil/water interfacial tension, the two-phase region became wider, residual oil saturation decreased, water relative permeability at residual oil saturation increased, and ultimate oil recovery increased.

Moreover, the relative permeability of oil phase increases with the decrease of interfacial tension, but the relative permeability of water phase (within endpoint) is not affected.

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REFERENCES

Adams W.T., and Schievelbein V.H. Surfactant Flooding Carbonate Reservoirs. SPE Reservoir Engineering 619-626,1987.

Adibhatia B., and Mohanty K.K. Simulation of surfactant-aided gravity drainage in fractured carbonates. SPE Reservoir Simulation Symposium, Houston, February 26-28, 2007.

Babadagli T., Al-Bemani A., Boukadi F., et al. A Laboratory Feasibility Study of Dilute Surfactant Injection for the Yibal Field, Oman. Journal of Petroleum Science and Engineering 48 (1): 37-52, 2005.

Bortolotti V., Macini P., and Srisuriyachai F. Wettability index of catbonatic reservoirs and EOR: laboratory study to optimize alkali and surfactant flooding. International Oil and Gas Conference and Exhibition in China, Beijing, June 8-10, 2010.

Liu A.W., and Li X.W. Two phase percolation characteristics in low permeability reservoirs and its influence. Journal of Oil and Gas Technology, 28(3):325-327, 2006.

Liu Q., Dong M., and Ma S. Alkaline/surfactant flood potential in western Canadian heavy oil reservoirs. SPE/DOE Symposium on Improved Oil Recovery, Tulsa, April 22-26, 2006.

Mantique E.J., Muci, V.E., and Gurfinkel M.E. EOR field experiences in carbonate reservoirs in the United States. SPE/DOE Symposium on Improved Oil Recovery, Tulsa, April 22-26, 2006.

Mohan K. Alkaline surfactant flooding for tight carbonate reservoirs. SPE Annual Technical Conference and Exhibition, New Orleans, October 4-7, 2009.

Seethepalli, A., Adibhatla, B., and Mohanty, K. K. 2004. Wettability Alteration During Surfactant Flooding of Carbonate Reservoirs. SPE 89423.

Sun C.H., Liu W.D., and Tian X.C. An Alkaline/Surfactant System for Injection Well Stimulation in Low Permeability and High Temperature Oil Reservoirs. Oilfield Chemistry 26(4):419-421,2009.

Torabzadeh S.J., and Handy L.L. The effect of temperature and interfacial tension on water/oil relative permeabilities of consolidated sands. SPE Enhanced Oil Recovery Symposium, Tulsa, April 15-18, 1984.

Wang Y. D., Wang S. H., and Jiang Z. J. The influence of temperature and interfacial tension on oil-water relative permeability. Oil Gasfield Surface Engineering, 23(4):11-12, 2004.

Yin D., Gao P., Pu H., and Zhao X. Investigation of a new simulator for surfactant floods in low permeability reservoirs and its application in Chao-522 field, 2010 update. SPE EOR Conference at Oil & Gas West Asia, Muscat, April 11-13, 2010.

Zeng B.Q., Chen L.S., and Hao F. Experiment and mechanism analysis on threshold pressure gradient with different fluids. The 34th Annual SPE International Conference and Exhibition, Calabar, Nigeria, July 31-Aug 7, 2010.

Zeng L.B., Qi J.F., and Li Y.G. The Relationship Between Factures and Tectonic Stress Field in the Extra Low-permeability Sandstone Reservoir at the South of Western Sichuan Depression. Journal of China University of Geosciences 18M:223-231, 2007.

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[1] Lin Zhao, Aifen Li, Kai Chen, et al. Development and evaluation of foaming agents for high salinity tolerance. Journal of Petroleum Science and Engineering, 81: 18-23, 2012.

[2] Zhao Lin, Li Aifen, Li Huihui et al. Evaluation on interfacial properties and displacement effect of tri-quaternary ammonium salt. Petroleum Geology and Recovery Efficiency, 19(1):72-74, 2012.

[3] Xiongjun Wu, Lin Zhao, Xiaojun Wang, et al. Synthesis and applications of Tri-quaternary ammonium salt Gemini surfactant. Journal of Dispersion Science and Technology, 34(1):106-110, 2013.

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[1] Li Ai-fen, Chen Kai, Zhao Lin, et al. Optimization and visualization of the injection patterns of foam system. Journal of Xi'an Shiyou University (Natural Science Edition), 26(5):49-52, 2011.

[2] Li Ai-fen, Zhang Dong, Yao Jun, et al. Physical simulation of waterflooding in fractured-vuggy unit. Journal of China University of Petroleum, 36(2):130-135,2012.

[3] Li Ai-fen, Fan Tian-you, Zhao Lin. Experimental study of spontaneous imbibition in low permeability core fractured reservoir. Petroleum Geology and Recovery Efficiency, 18(5): 67-69,2011.

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[1] Xiongjun Wu, Lin Zhao, Xiaojun Wang, et al. Synthesis and applications of Tri-quaternary ammonium salt Gemini surfactant. Journal of Dispersion Science and Technology, 34(1):106-110, 2013.

[2] Xiong-Jun Wu, Guan-Cheng Jiang, Xiao-Jun Wang, et al. Prediction of reservoir sensitivity using RBF neural network with trainable radial basis function. Neural Computing and Applications, 22(5):947-953, 2013

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